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Characteristics of aggregates used in road construction in Portugal, complying with the requirements of European Conformity (CE marking)

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Abstract

In the context of European Conformity (CE marking), an inventory on the aggregates used in road construction in Portugal, encompassing 145 producers (68%) and 228 production centres (79%) was carried out, aiming to support the normalisation of activity for aggregates. A broad and representative characterisation of the geometric, physical, mechanical, chemical, and weathering properties of the aggregates was obtained. A total of 106 aggregate sizes allowed the delineation of two predominant dimensional combinations. Aggregates showed dependence on the lithological type, especially with respect to geometrical, physical, and mechanical properties. More than 30% of the all-in aggregates did not satisfy the sand equivalent category SE50 and the methylene-blue category MB2.5, requiring great care in the establishment of specifications. For high levels of performance, in terms of mechanical resistance, the percentage of aggregates satisfying the Los Angeles category LA30 and the polished stone value category PSV50 was quite low. Comparisons with other countries were not possible as no similar data compilation or inventory was found. The present research aims at improving the application of European aggregate standards and, hopefully, at triggering similar work in other countries, especially European ones, in order to contribute to new international standards or to the revision of those standards currently in force.

Keywords

Aggregate
Inventory of characteristics
CE marking
Portugal

Introduction

Aggregates are an extensively used raw material and are mainly consumed in close proximity to production centres, because of the significant cost increase when significant transport distances are required. According to Kaliampakos and Benardos (1999), delivering aggregates to a distance of 15 km from the quarry leads to a 30% price increase and a delivery distance of more than 40 km is unusual (Drew et al. 2002). The consumption of aggregates is closely related to the economic performance of a country, which is measured as gross domestic product per capita (GDP/capita), since various productive sectors depend on quarrying (Menegaki and Kaliampakos 2010; Balletto and Furcas 2011; Neves et al. 2015). The GDP from construction is also a safe indicator of aggregates production (Drew et al. 2002). In the European Union (EU) the aggregates industry is the largest non-energy extractive sector with an output of 2.6 billion tonnes/year, and an annual turnover of 15 billion euros in the 28 EU members plus EFTA countries (UEPG 2014–2015). Of the 28 EU members, Germany, France, and the UK are the largest producers of aggregates. Annual per capita production varies widely depending on the development and characteristics of each European country (Menegaki and Kaliampakos 2010).

In the EU, the Directive of Construction Products (EEC 1989, 2011) and related harmonised standards are now mandatory, nullifying national specifications for aggregates in force until 2004. As observed by Branco et al. (2015), a review of the regulatory framework has been undertaken. This encompasses the standards for the use of aggregates, namely for concrete, mortar, bituminous mixtures, unbound mixtures, and aggregates treated with hydraulic binders, and requires an extensive review of technical specifications. It is also essential to know the properties of the aggregates produced for the establishment of new threshold values.

A bibliographic search found no systematic information on the properties of aggregates produced in the EU, in the context of the Directive on Construction Products and the European Conformity (CE marking). This gap motivated the development of an exhaustive survey in Portugal.

The procedure adopted in the survey (Branco et al. 2015) involved three main steps: (1) contact with the notified bodies to obtain a list of certified companies conforming to the CE marking; (2) preparation of a questionnaire to collect information from aggregate producers, mailing of the questionnaire, and compilation of the responses to the survey and the product technical data sheets; and (3) a bibliographic search to gather characterisation data of the aggregates produced in Portugal that could complement and validate the data collected from producers (Branco et al. 2006; Freire and Antunes 2007).

The data survey was directed at aggregate producers who were certified under the CE marking by 30 October, 2008, was conducted through an inquiry described in detail by Branco et al. (2015), and supplemented by CE marking documents including certificates, declarations of conformity, and technical data sheets. Producers were also asked to supply a petrographic description of their aggregates (Branco and Quinta-Ferreira 2009, 2011).

The benefits provided by the inquiry are as follows (Branco et al. 2015):

- Useful information was provided for defining the limits of the different parameters and fields of application, seeking to balance performance and real supply capacity of the materials meeting the specification;
- Data for benchmarking was provided for producers;
- Useful information was provided for designers and constructors for the selection of parameters and/or materials to be specified and used in construction; and
- Information for the scientific community was provided, allowing a better understanding of aggregates produced in Portugal and attracting the interest of researchers in further development of some of the issues addressed in the study.

It would be very useful if other countries in the European Union performed similar research to allow broader comparisons and an understanding of local and national variability of aggregate characteristics complying with the requirements of CE marking.

Scope of the study

Rock outcrops are abundant in Portugal, presenting a quite diverse lithology including sedimentary, igneous, and metamorphic rocks. The widespread presence of rocks allows aggregates to be produced all over the country (including the mainland, the Azores, and Madeira).

Of the 213 certified companies, 200 (93.9%) were contacted. Thirteen small companies had to be excluded from the survey because of the impossibility of getting into contact with them. From the companies contacted, 145 responded favourably, which corresponds to 72.5%. In the cases where a company did not respond to the inquiry, but its website contained product data sheets, those data were also considered. The number of production centres covered by the study was 228, from a total of 289, which corresponds to 78.9%. The survey covered the entire Portuguese territory, including all 18 districts and the two autonomous regions of Madeira and the Azores. Table 1 shows the distribution of the responses received according to geographical location. Table 2 shows the distribution of the production centres and the products covered by the CE conformity certification, arranged by standard.

Table 1

Geographical distribution of production centres that responded to the inquiry

Region	Production centres	%
Santarém	30	13.2

Region	Production centres	%
Porto	27	11.8
Lisbon	20	8.8
Setúbal	18	7.9
Leiria	14	6.1
Coimbra	12	5.3
Braga	11	4.8
Viseu	11	4.8
Bragança	10	4.4
Faro	9	3.9
Évora	9	3.9
Madeira	9	3.9
Viana do Castelo	9	3.9
Azores	8	3.5
Aveiro	7	3.1
Beja	6	2.6
Guarda	6	2.6
Vila Real	5	2.2
Castelo Branco	4	1.8
Portalegre	3	1.3
Total	228	100.0

Table 2

Number of production centres and products, arranged by standard

Standard	Scope	Production centres	%	Products	%
EN 12620 (EN 12620:2002+A1:2008, 2008)	Aggregates for concrete	215	94.3	1152	67.8
EN 13043 (EN 13043:2002, 2002)	Aggregates for bituminous mixtures	180	78.9	1012	59.5
EN 13055–1 (EN 13055-1:2002, 2002)	Lightweight aggregates for concrete. Mortar and grout	2	0.9	13	0.8
EN 13055–2 (EN 13055-2:2004, 2004)	Lightweight aggregates for unbound and bound applications	1	0.4	1	0.1
EN 13139 (EN 13139:2002/AC:2004, 2004)	Aggregates for mortar	125	54.8	311	18.3
EN 13242 (EN 13242:2002+A1:2007, 2007)	Aggregates for unbound and hydraulically bound materials	194	85.1	1117	65.7
EN 13383 (EN 13383-1:2002/AC:2004, 2004)	Armourstone	53	23.2	76	4.5
EN 13450 (EN 13450:2002/AC:2004, 2004)	Aggregates for railway ballast	8	3.5	11	0.6
Total		228(a)	100.0	1700(b)	100.0

(a)A production centre can manufacture according to several standards.

(b)A product can comply with several standards.

Products with CE marking appear in the four most common fields of application in Portugal: concrete (EN 12620), granular bases (EN 13242), bituminous mixtures (EN 13043), and mortar (EN 13139). On average, each production centre has more than five products for EN 12620, EN 13242, EN 13043, and EN 13055–1. For the other standards, the number of products by production centre is below 2.5.

Armourstone (EN 13383) is manufactured in 53 production centres (23%), but it is only 4.5% of the total produced. Aggregates for railway ballast (EN 13450) are manufactured in eight production centres (3.5%), but the number of products is only 0.6% of the total. Producers of lightweight aggregates (EN 13055–1 and EN 13055–2) are rare in Portugal, with only a residual significance in the study.

The certified producers were surveyed, regardless of the type of aggregate they produce: natural, artificial, or recycled. Replies to the questionnaire were received from producers of natural aggregates, fillers, recycled aggregates (produced from construction and demolition waste), and artificial aggregates (expanded clay). No reply was received from steel slag aggregate producers. The distribution of replies by aggregate type shows an almost total dominance of natural aggregates with 225 cases, while the recycled and artificial aggregates had two cases each. The 228 production centres actually correspond to 229 cases because one of the natural aggregates production centres produces two different aggregate types.

The main rock types used in the production of natural aggregates in Portugal were covered. Table 3 shows the distribution of the aggregates produced by lithology. It is evident that aggregates produced from granite, alluvium, and limestone are predominant. Basaltic aggregates are the only ones available on the volcanic islands of the Azores and Madeira, and are rarely found on the mainland.

Table 3

Distribution of production centres by lithology

Rock group	Lithology	Production centres	%	%
Plutonic igneous rocks	Granite	81	36.0	
	Granodiorite	3	1.3	
	Gabbro	2	0.9	39.6
	Gabbro diorite	1	0.4	
	Syenite	1	0.4	
	Gneiss[(a)]	1	0.4	
Natural sands and gravel	Sand	34	15.1	25.3
	Gravel	23	10.2	
	Limestone	50	22.2	
Carbonate rocks	Marble	4	1.8	24.9
	Dolomite	2	0.9	
Volcanic rocks	Basalt	19	8.4	9.3
	Rhyolite/Dacite	2	0.9	
Other	Greywacke	1	0.4	0.9
	Barite[(b)]	1	0.4	
Total		225		
(a) Gneiss is not a plutonic igneous rock, but it was included in this group because of its mineralogical similarity to granite.				
(b) The mineral barite is not currently used in the production of aggregates except fillers, as is the case included in this study.				

Results

The survey covered all products of the companies contacted, and therefore data for all kinds of applications were collected. Despite this fact, the results presented here relate to only the most relevant fields of application for road works and concern EN 12620, EN 13043, and EN 13242, which are the standards most frequently used in Portugal (Table 2). Aggregates used in railways, such as ballasts (EN 13450), aggregates applied in hydraulic structures such as armourstone (EN 13383), aggregates applied in mortars (EN 13139), and lightweight aggregates (EN 13055–1 and EN 13055–2) were excluded.

Geometrical properties

Among the geometrical properties, those with greater importance for road specifications will be highlighted, namely grain size, flakiness index, shape index, and the quality of the fines evaluated by the sand equivalent test (SE) and the methylene blue test (MB).

Grain size

The data collected suggest that very different approaches were adopted by producers in the granulometric characterisation of their aggregates, particularly with regard to the declared granulometric requirements. All of them declared the aggregate size (d/D), which is the designation of the aggregate in terms of lower (d) and upper (D) sieve sizes. Almost all producers declared the category relative to general requirements (d/2, d, D, 1,4D and 2D). Almost all, but fewer than above, declared the category of the fines content (< 0.063 mm). Those producers who declared the typical grain size distribution and the tolerance of the intermediate sieve (D/1,4 or D/2) were considerably fewer. These results were expected, since the less-declared requirements are those that the harmonised standards do not define as mandatory.

The complete dataset related to the grain size requirements will not be presented, as it does not allow any significant analysis. It was considered sufficient to point out some aspects related to aggregate size (d/D), as some opportunities for improvement can be highlighted.

Of the 1700 product technical data sheets analysed, 106 different aggregate sizes were identified. The aggregate size distribution was organised into dimensional groups as follows: 1 for fillers, 6 for fine aggregates, 74 for coarse aggregates, 13 for all-in aggregates, and 12 for armourstone.

The most common group sizes are presented in Table 4. In the group, “Fine aggregate”, dimensions up to 0/6 were considered, although this limit isadopted only for unbound mixtures (EN 13242). This limit was adopted because it seems to be the one best suited to separate the fine aggregate from the all-in aggregate produced in Portugal.

Table 4

Most frequent aggregate sizes

Most frequent sizes (d/D)		**Frequency (%)**		
Aggregate type	**d/D**[(a)]	**Inside the size group**	**In general**	
Filler aggregate	0/0.063	100	1.4	1.4
Fine aggregate	0/2	14.6	3.5	20.5
	0/4	57.4	13.6	
	0/6	14.1	3.4	
Coarse aggregate	2/6	3.9	2.0	35.2
	4/6	4.8	2.5	
	4/8	2.8	1.4	
	4/10	4.8	2.5	
	4/12	3.3	1.7	
	4/16	2.0	1.0	
	6/12	4.0	2.1	
	6/14	5.3	2.7	
	8/16	2.4	1.2	
	10/20	3.3	1.7	
	11/22	5.5	2.8	
	12/20	4.8	2.5	
	14/20	4.0	2.1	
	16/32	3.0	1.5	
	20/32	4.7	2.4	
	20/40	6.8	3.5	
	32/63	3.1	1.6	
All-in aggregate	0/32	60.9	11.7	15.1
	0/40	17.4	3.4	
Armourstone	0/250	19.5	0.9	3.6
	63/180	10.4	0.5	
	90/180	22.1	1.0	

Most frequent sizes (d/D)		Frequency (%)	
Aggregate type	**d/D**	**Inside the size group**	**In general**
	90/250	27.1	1.2

[a] Lower (d) and upper (D) sieve sizes.

The analysis of the data allowed identification of the two most common aggregate size combinations:

- Combination 1: Fine aggregate: 0/4 mm; Coarse aggregate: 4/6, 6/12, 12/20, 20/32 mm; All-in aggregate: 0/32 mm
- Combination 2: Fine aggregate: 0/4 mm; Coarse aggregate: 4/6, 6/14, 14/20, 20/40 mm; All-in aggregate: 0/40 mm

For these two combinations, the fractions 0/2 and/or 0/6 can still apply. The size 0/2 is very common in plants that produce sands, whether natural or crushed. The size 0/6 is quite frequent when the size 4/6 is not produced, or when this dimension is produced by complementary arrangements.

For the construction sector, it would be beneficial if aggregate producers were to reduce the diversity of products and normalise aggregate size, especially for the certification of both concrete and bituminous mixtures, allowing the stabilisation of the mixtures' characteristics even if the supplier of the aggregate changes.

The analysis of the 1700 product data sheets identified a number of incorrect size declarations for aggregates, namely:

- infringement of the requirement $D/d \geq 1.4$;
- use of unforeseen diameters, such as 25, 28, 30, 35, and 50 mm; and
- simultaneous use of sieves of the Base +1 and Base +2 series.

It is worth noting that the number of cases of incorrect identification of the aggregate size is not very high. From a total of 1700 technical data sheets and corresponding CE certificates of conformity, only 19 incorrect cases (1.1%) were detected.

Flakiness and shape

Of the three parameters specified by the harmonised standards to characterise the aggregate particles shape, flow coefficient for fine aggregates, flakiness index, and shape index for coarse aggregates, only the last two parameters have been used in Portugal. For the coarse aggregate, a preference for the flakiness index was identified (Table 5). This preference was minimal for the all-in aggregates.

Table 5

Production centres that declared performance concerning the shape

Size group	Total of production centres	Production centres that declared shape properties			
		Flakiness index		Shape index	
Coarse aggregate	179	141	79%	117	65%
All-in aggregate	155	94	61%	91	59%

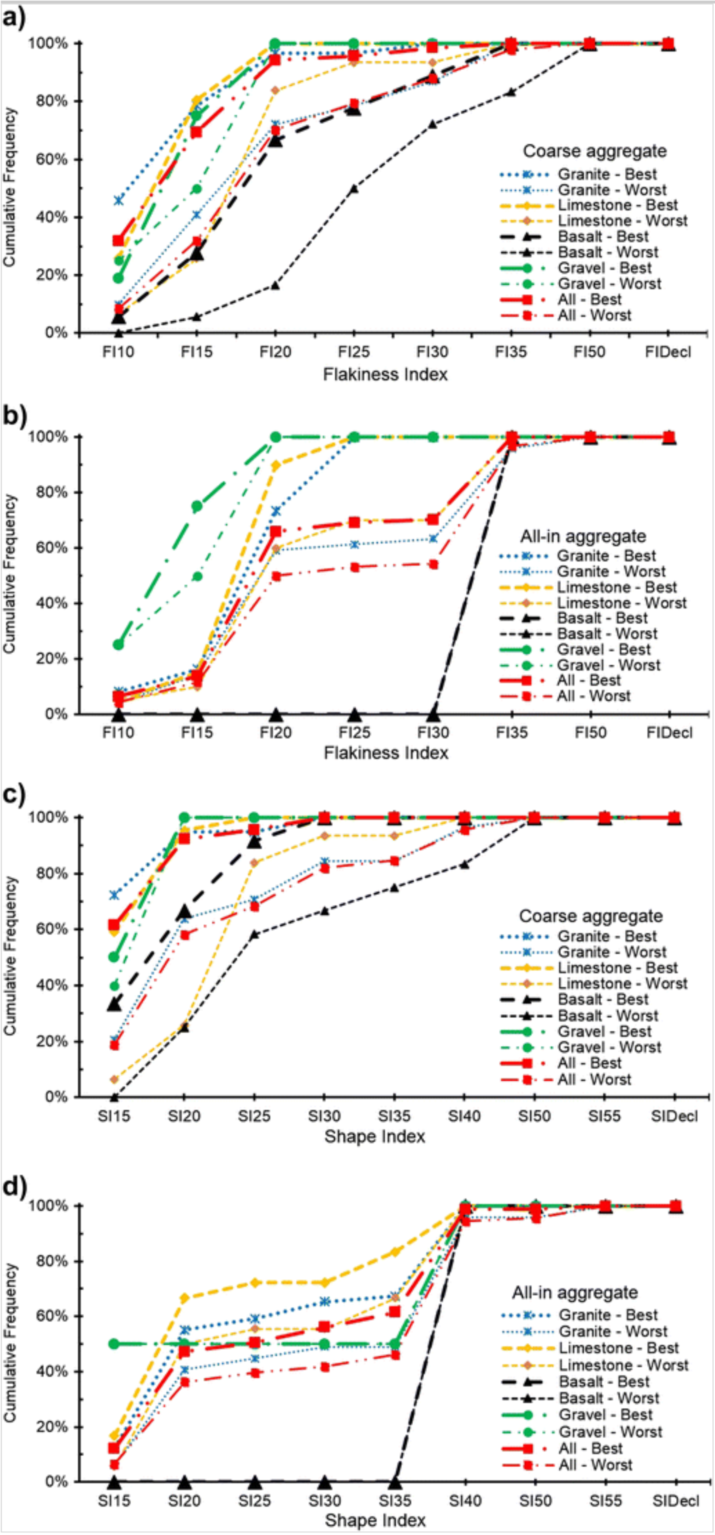
The difference observed between the percentages of producers who declared the performance of coarse aggregate and of all-in aggregate might be related to the way in which these requirements are presented in the harmonised standards. A simplistic reading of these standards can lead to the wrong conclusion that these parameters only apply to coarse aggregate. However, they are also applicable to all-in aggregate since, by definition, this aggregate is composed of fine aggregate and coarse aggregate.

Different performances for diverse quarry products were declared by the producers. Given the high number of products and the consequent difficulty of appropriately analysing each product, the analysis was done taking into account the "best" and "worst" performances declared by producers for all products of each production centre.

The performance distribution declared by the producers is presented in Fig. 1 in relation to the two parameters that characterise the shape of aggregates, i.e., flakiness index (Fig. 1a and b) and shape index (Fig. 1c and d), grouped by the categories defined by the harmonised standards. As the categories defined in the standards are not coincident, it was decided to consider all categories. The frequencies presented are cumulative, as they allow better data analysis. For this purpose, it was assumed that an aggregate that fulfils a certain category (e.g., the FI_{15} category, which corresponds to a flakiness index ≤15%) also meets the subsequent categories, which are less demanding (e.g., the FI_{20} and FI_{25} categories).

Fig. 1

Performance of aggregate types, by lithology, related to particle shape. For the flakiness index: (a) coarse aggregate, (b) all-in aggregates. For the shape index: (c) coarse aggregate, (d) all-in aggregate



The curves of cumulative frequency for the flakiness index show a smooth and gradual trend for coarse aggregate, while they form plateaus for the all-in aggregates. The exception seems to be gravel, which shows similar distribution curves in both cases. The most evident discrepancy occurs for the all-in basalt aggregates, showing a 0% frequency until FI30, changing abruptly to 100% for FI35, with "best" and "worst" curves coinciding. Excluding gravel and basalt, all the other all-in aggregate lithologies exhibit low cumulative frequency until FI15, increasing abruptly for FI20. Granite all-in aggregates present a distinct plateau between FI20 and FI30 (granite "worst") before reaching 95% for FI35. Limestone "best", on the other hand, reaches 100% for FI25. For the limestone and granitic aggregates, the curves for "best" and "worst" can be considered roughly similar, with the limestone presenting slightly higher values of cumulative frequencies.

The charts for shape index are also quite different for the coarse and the all-in aggregates and, again, are more regular for coarse aggregates. Concerning the shape index for coarse aggregates, only the “best” curves reach a cumulative frequency of 100% for SI30, while for the “worst” curves, the 100% values are achieved only at SI40 for the limestone, or even at SI50 for granite and basalt. The shape index for most of the all-in aggregates shows a plateau between SI20 and SI35, with their cumulative frequency values around 40% for granite “worst” and 70% for limestone “best”, and reaching around 100% for SI40. Two exceptions are basalt and gravel. Basalt shows a cumulative frequency of zero until SI35, reaching 100% for SI40. Gravel exhibits 50% cumulative frequency from SI15 to SI35, while all the other aggregates have frequencies lower than 20% for SI15. For the all-in aggregates of all lithological types, a cumulative frequency around 100% is reached for SI40.

The analysis of the four charts in Fig. 1 suggests that there is some dependence between the aggregates’ shapes and their lithological natures. For example, the basalt aggregates perform worse than the other aggregates and the limestone aggregates have a slightly better performance than granite aggregates. This should be related to the different crushing procedures that are usually used based on rock abrasiveness. For low abrasiveness rocks (e.g., limestone) the fragmentation is mainly done by impact. For high abrasiveness rocks (e.g., basalt and quartzite) the fragmentation is mainly done by crushing, which generates more elongated and flatter particles.

The charts of Fig. 1 are useful in establishing the limiting values for acceptance/rejection as they allow the identification of the percentage and type of aggregates that meet a specified value.

Quality of fines

Table 6 identifies the number of production centres that declared performance related to the quality of fines for fine aggregate and all-in aggregate, as recommended by the harmonised standards, namely:

- as part of the standards EN 12620, EN 13139, and EN 13242: sand equivalent (SE) of the fraction 0/2 mm, SE_4—sand equivalent of the fraction 0/4 mm, methylene blue (MB) of the fraction 0/2 mm; and
- for the standard EN 13043: MB_F—methylene blue of the fraction 0/0.125 mm.

Table 6

Production centres that declared performance related to the quality of fines

Aggregate type	Number of production centres	Declared quality of fines(a)							
		SE		SE_4		MB		MB_F	
Washed fine aggregate	122	51	42%	2	2%	25	20%	(b)	
Unwashed fine aggregate	142	84	59%	2	1%	61	39%	93	65%
Higher quality all-in aggregate	155	100	65%	2	1%	59	38%	(b)	
Lower quality all-in aggregate	94	55	59%	0	0%	38	40%	(b)	

(a)SE—sand equivalent of the fraction 0/2 mm; SE_4–SE fraction 0/4 mm; MB—methylene blue of the fraction 0/2 mm; MB_F–MB fraction 0/0.125 mm.

(b) Washed aggregate and the all-in aggregate are very rarely included in the scope of standard EN 13043, and therefore the parameter MB_F was considered not to apply.

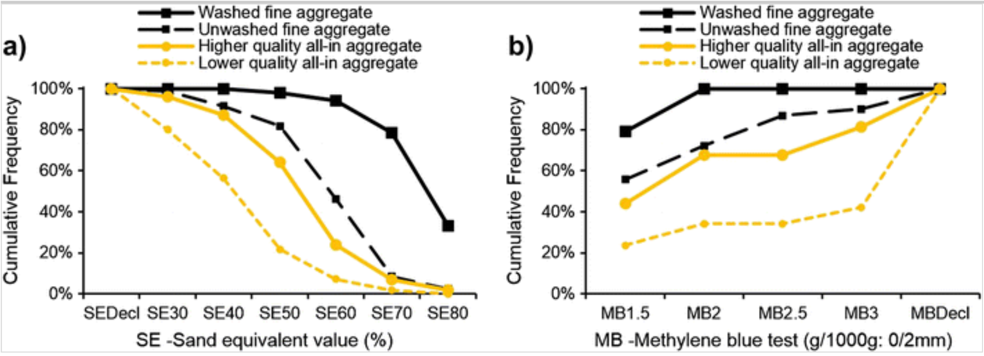
For standards EN 12620, EN 13139, and EN 13242, a clear preference for the SE instead of the MB can be observed, probably justified by the greater experience in Portugal in the use of the SE. The use of SE_4 is residual, because the harmonised standards consider it a subsidiary of the SE parameter, which is the reference for evaluating the quality of the fines in the SE test.

In the case of unwashed fine aggregate, the more frequent use of MB_F relates to the fact that these products are more often certified in accordance with standard EN 13043, a standard that specifies MB_F as the unique parameter for assessing the quality of fines. Another point that may justify the significant number of producers declaring the performance of their aggregates in respect to MB_F is that the minimum test frequency set out in EN 13043 is biannual, while the frequency recommended by other harmonised standards for the SE and MB is weekly.

Figure 2 presents the cumulative frequency of the performance declared by producers concerning the quality of fines, as expressed by the SE, Fig. 2a, and by the MB, Fig. 2b. The data were grouped by type of aggregate: washed fine aggregate, unwashed fine aggregate, higher quality all-in aggregate, and lower quality all-in aggregate.

Fig. 2

Performance of aggregate types by lithology, related to the quality of fines: (a) for the sand equivalent value (SE), (b) for the methylene blue test (MB)



The charts in Fig. 2 are consistent with each other, expressing the expected differences in performance for different materials. They show better performance of washed fine aggregate relative to unwashed, better performance of the fine aggregate relative to the all-in aggregate, and better performance of the all-in aggregate of higher quality in relation to that of lower quality. In fact, the curves of “washed fine aggregate” and “higher quality all-in aggregate” are shifted to the right for the sand equivalent value in relation to the “unwashed” and “lower quality”, denoting that cumulative frequency around 100% is maintained for higher SE values, e.g., SE60 for washed aggregates, while for unwashed aggregates similar values are observed only through SE30. For the methylene blue test, the curves develop almost parallel to each other, with cumulative differences between “higher quality” and “lower quality” all-in aggregate more evident than for “washed” and “unwashed” fine aggregate. The lowest value of cumulative frequency is observed for “lower quality all-in aggregate”, being slightly above 20% for MB1.5.

Mechanical properties

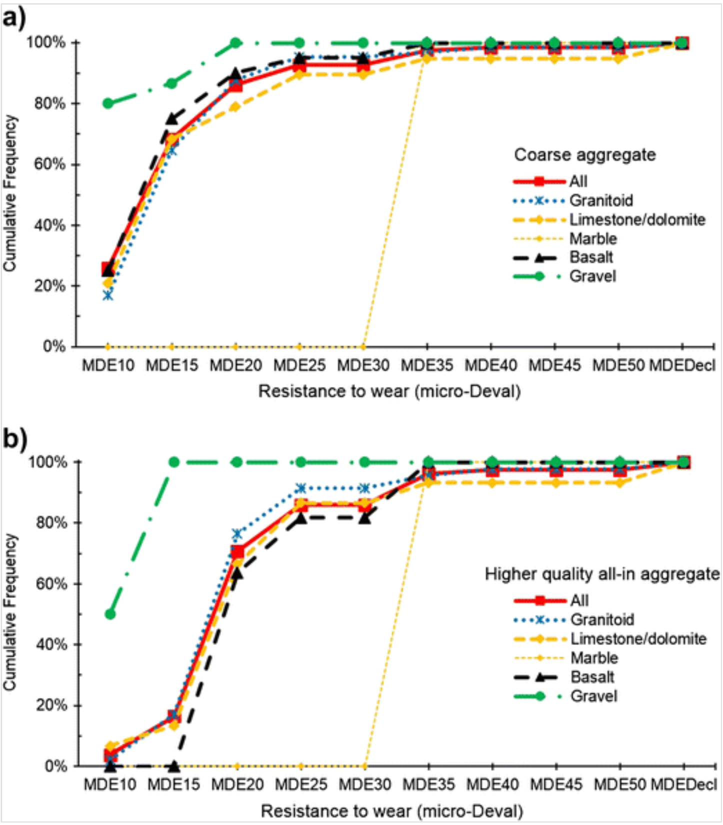
Among the mechanical properties, those having greater importance in road specifications will be highlighted, particularly the resistance to wear (micro-Deval coefficient), resistance to fragmentation (LA coefficient), and resistance to accelerated polishing (Polished Stone Value, the PSV coefficient).

Resistance to wear (micro-Deval coefficient)

The number of production centres that reported the performance of their aggregates in relation to resistance to wear was 122 out of 179 (68%) in the case of coarse aggregates, and 80 out of 155 (52%) in the case of all-in aggregates (75%). It is worth noting the high level of use of the micro-Deval test (M_{DE}), since the harmonised standards mean it is not compulsory to declare performance, and in Portugal there was no tradition of using this parameter. The accumulated frequencies for resistance to wear declared by producers are presented in Fig. 3a for the coarse aggregate and in Fig. 3b for the higher quality all-in aggregate. The data presented were organised by aggregate type and lithology. Regarding the lithological nature of the aggregates, five groups were considered: granitoid (including granite and other plutonic rocks such as gabbro, diorite, granodiorite, syenite, and gneiss), limestone/dolomite, marble, basalt (volcanic rocks *s.l.*, including rhyolite and dacite), and gravel.

Fig. 3

Resistance to wear (M_{DE}) of aggregate types by lithology: (a) for coarse aggregates, (b) for higher quality all-in aggregates



Both for the coarse aggregate and the all-in aggregate, it appears that the gravel and marble differ significantly from the other lithologies. The gravel aggregate shows the best performance, both for coarse aggregate and for all-in aggregate, while the marble aggregate presents the worst performance. The remaining lithological types (granitoids, limestone/dolomite, and basalt) show similar results. A cumulative frequency around 100% is attained in both groups of aggregates for MDE35. The curves of marble are similar for the coarse aggregate and the all-in aggregate, showing 0% until MDE30 and then increasing in a single step to 100%, showing a quite different pattern from the other lithologies.

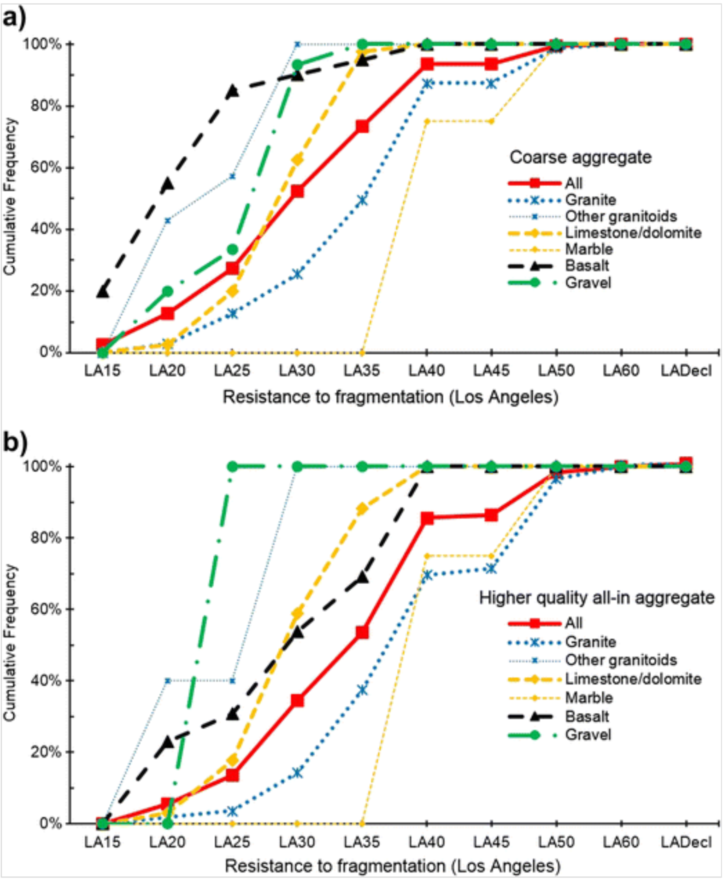
Resistance to fragmentation (Los Angeles coefficient)

The number of production centres that reported the performance of their aggregates in relation to resistance to fragmentation was 159 out of 179 (89%) in the case of coarse aggregates, and 117 out of 155 (75%) in the case of all-in aggregates. Comparing the number of production centres declaring resistance to fragmentation (LA) with the number of centres declaring the resistance to wear (micro-Deval), it was concluded that the former is significantly higher. This is not surprising, since most Portuguese specifications assume the resistance to fragmentation as an indication of the mechanical quality of aggregates.

The charts in Fig. 4 show the distribution of the performance declared by the producers in relation to the resistance to fragmentation (LA) and in terms of cumulative frequencies for coarse aggregate (Fig. 4a) and for higher quality all-in aggregate (Fig. 4b). The data were organised by lithological group, taking into account the aggregate type, in a similar way to the procedure that was used for the resistance to wear. An amendment to the lithological groups previously considered was introduced, splitting the granitoid group into two subgroups, one composed exclusively of granite and the other named “other granitoids” including the remaining plutonic rocks and gneiss. This change was justified by the quite different performances of these two subgroups, as can be observed in Fig. 4.

Fig. 4

Resistance to fragmentation (LA) of aggregate types by lithology for: (a) coarse aggregates, (b) higher quality all-in aggregates



The differentiation in aggregate performance by lithological type is more evident for resistance to fragmentation (LA) (Fig. 4) than for resistance to wear (M_{DE}) (Fig. 3). Note that basalt, gravel (alluvial), and the granitoids perform better than the rest of the coarse aggregates. The granite and the marble aggregates show the worst performances, while limestone/dolomite aggregates have intermediate performances. Among the coarse aggregate, basalt shows the highest cumulative frequencies until LA25. For the higher quality all-in aggregate, the granitoids and gravel exhibit the best performances. Gravel shows the steepest curve, from a cumulative frequency of zero for LA20 up to 100% for LA25.

Table 7 shows the geographic distribution of the performance of coarse aggregates for resistance to fragmentation (LA), considering for this purpose the 18 districts and the two autonomous regions (Madeira and the Azores). In this context, the lithological nature of the aggregates produced in each region was also identified.

Table 7

Geographical distribution of resistance to fragmentation (LA)

Region	Lithology		Declared by property		Resistance to fragmentation (LA coefficient) category Cases Frequency (%) Cumulative Frequency (%)									
			Cases	%	LA_{15}	LA_{20}	LA_{25}	LA_{30}	LA_{35}	LA_{40}	LA_{45}	LA_{50}	LA_{60}	LA_{Dec}
Viana do Castelo	Granite	5	4	80%				3		2				
	Gravel	2	1	20%				60%		40%				
	Granodiorite	1	0	0%				60%	60%	100%	100%	100%	100%	100%
Braga	Granite	9	8	89%			1	2	2	2		1		1
	Granodiorite	1	1	11%			11%	22%	22%	22%		11%		11%
	Recycled	1	0	0%			11%	33%	56%	78%	78%	89%	89%	100%
Vila Real	Granite	5	5	100%			1		1	1		2		
							20%		20%	20%		40%		
							20%	20%	40%	60%	60%	100%	100%	100%
Bragança	Granite	8	8	80%		1		1	1	7				
	Gabbro	1	1	10%		10%		10%	10%	70%				
	Gravel	1	1	10%		10%	10%	20%	30%	100%	100%	100%	100%	100%
Porto	Granite	25	25	96%			2	3	12	7		2		

Region	Lithology		Declared by property		Resistance to fragmentation (LA coefficient) category Cases Frequency (%) Cumulative Frequency (%)									
			Cases	%	LA	LA	LA	LA	LA	LA	LA	LA	LA	LA
	Gravel	2	1	4%			8%	12%	46%	27%		8%		
							8%	19%	65%	92%	92%	100%	100%	100%
Aveiro	Granite	3	2	50%		1	1	1	1					
	Gneiss	1	1	25%		25%	25%	25%	25%					
	Gravel	1	1	25%		25%	50%	75%	100%	100%	100%	100%	100%	100%
Viseu	Granite	11	10	100%				1	1	5		3		
								10%	10%	50%		30%		
								10%	20%	70%	70%	100%	100%	100%
Guarda	Granite	6	3	100%			1			2				
							33%			67%				
							33%	33%	33%	100%	100%	100%	100%	100%
Castelo Branco	Granite	4	2	100%			1			1				
							50%			50%				
							50%	50%	50%	100%	100%	100%	100%	100%
Coimbra	Limestone	5	3	75%			1	1	1	1				
	Granite	1	1	25%			25%	25%	25%	25%				
	Gravel	2	0	0%			25%	50%	75%	100%	100%	100%	100%	100%
Leiria	Limestone	6	4	50%		1	4	3						
	Gravel	4	4	50%		13%	50%	38%						
						13%	63%	100%	100%	100%	100%	100%	100%	100%
Santarém	Limestone	9	8	53%	1	6	4	4						
	Gravel	7	6	40%	7%	40%	27%	27%						
	Basalt	1	1	7%	7%	47%	73%	100%	100%	100%	100%	100%	100%	100%
Portalegre	Granite	2	2	100%				1	1					
	Dolomite	1	0	0%				50%	50%					
								50%	100%	100%	100%	100%	100%	100%
Lisbon	Limestone	13	10	71%	2	1		3	7	1				
	Basalt	2	2	14%	14%	7%		21%	50%	7%				
	Gravel	2	2	14%	14%	21%	21%	43%	93%	100%	100%	100%	100%	100%
	Recycled	1												
Setúbal	Limestone	6	6	75%		1	2	5						
	Granodiorite	1	1	13%		13%	25%	63%						
	Greywacke	1	1	13%		13%	38%	100%	100%	100%	100%	100%	100%	100%
Évora	Marble	4	4	50%		2		1	1	3		1		
	Granite	2	2	25%		25%		13%	13%	38%		13%		
	Granodiorite	1	1	13%		25%	25%	38%	50%	88%	88%	100%	100%	100%
	Dolomite	1	1	13%										
Beja	Rhyolite/Dacite	2	2	50%		2	1	1						
	Gravel	2	1	25%		50%	25%	25%						
	Gabbro	1	1	25%		50%	75%	100%	100%	100%	100%	100%	100%	100%
Faro	Limestone	8	8	89%				7	2					
	Syenite	1	1	11%				78%	22%					
								78%	100%	100%	100%	100%	100%	100%

Region	Lithology		Declared by property		Resistance to fragmentation (LA coefficient) category Cases Frequency (%) Cumulative Frequency (%)									
			Cases	%	LA	LA	LA	LA	LA	LA	LA	LA	LA	LA
Azores	Basalt	8	7	100%		1	3	1	1	1				
						14%	43%	14%	14%	14%				
						14%	57%	71%	86%	100%	100%	100%	100%	100%
Madeira	Basalt	8	8	100%	2	5	1							
					25%	63%	13%							
					25%	88%	100%	100%	100%	100%	100%	100%	100%	100%

The data presented in Table 7 can be very useful for specifying the limits of acceptance/rejection for the resistance to fragmentation, as they indicate whether there are production centres that meet a specified demand in each region. For example, the adoption of the LA_{20} category implies that the districts of Viana do Castelo, Braga, Vila Real, etc., cannot meet their needs with the quarries in the region. In contrast, the same specification does not pose major problems in the autonomous region of Madeira.

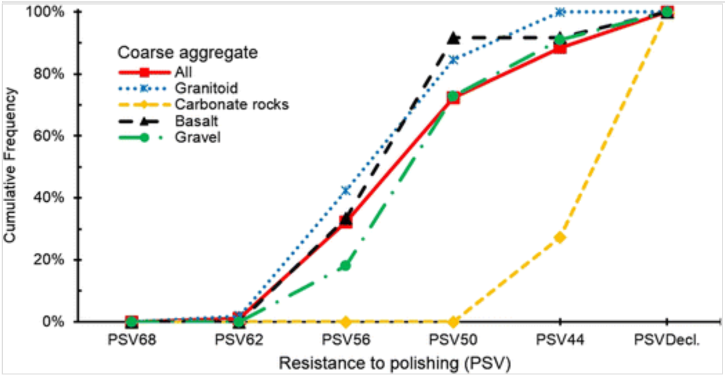
Resistance to polishing (polished stone value coefficient)

The number of production centres that reported the performance of their aggregates relative to polishing resistance was 87 out of 179 (49%). As for the LA, the PSV is a parameter required under Portuguese specifications, although the scope of its application is narrower, since it concerns only the materials used in surface layers of pavements. Certainly, this factor means that the number of production centres stating performance with respect to the PSV coefficient is significantly lower than the LA coefficient. For example, among the producers of limestone aggregates only a few integrated this parameter into their product data sheets.

Figure 5 shows the distribution of the performances declared by producers for resistance to accelerated polishing (PSV) in terms of accumulated frequencies, including the categories provided by the two harmonised standards that specify this parameter (EN 13043 and EN 12620). The data on resistance to polishing are organised by the lithology of the aggregate.

Fig. 5

Resistance to polishing (PSV) of coarse aggregates by lithology



As can be concluded from Fig. 5, limestone aggregate has the worst performance of all tested aggregates, which is why numerous road construction codes have forbidden limestone to be used in pavement surface layers. Among the other three lithological groups, a better performance of granitoid and of basaltic aggregates can be observed, compared to the performance of alluvial aggregate.

Conclusions

The results of the study are quite relevant for those working with aggregates under the CE marking. They provide a sound basis for decision making concerning the establishment of recommendations or the definition of reasoned rejection/acceptance limits, taking into account the effective needs of the different end uses and the real production capacity in different regions.

There are a large number of aggregate sizes, some of which diverge from the criteria in their normative references. Among the various dimensional groups, namely fillers, fine aggregate, coarse aggregate, all-in aggregate, and armourstone, 106 different aggregate sizes were recorded with a prevalence of two-dimensional combinations.

- Combination 1: Fine aggregate: 0/4 mm; Coarse aggregate: 4/6, 6/12, 12/20, 20/32 mm; All-in aggregate: 0/32 mm
- Combination 2: Fine aggregate: 0/4 mm; Coarse aggregate: 4/6, 6/14, 14/20, 20/40 mm; All-in aggregate: 0/40 mm

As expected, the shape of aggregates has some dependence on the lithological type. It was verified that the basaltic aggregates perform worse than the other aggregates. Limestone aggregates give a slightly better performance than granite aggregates. It should be noted that the shape of aggregates is greatly dependent on the manufacturing process, so achieving high levels of performance is possible for any lithological type, as long as the respective manufacturing processes are suitably adjusted by choosing adequate equipment and the appropriate number of crushing stages.

The preference of producers for the SE test surpassed the MB test. Regarding the performance levels reported, the number of all-in aggregates that did not meet SE_{50} and $MB_{2.5}$ categories exceeds 30%, and great care is recommended when specifications for these parameters are defined. The quality of fines is also highly dependent on the manufacturing process, with particular emphasis on the extraction phase.

Although the supply of quality aggregates in Portugal is good, there are some limitations when high levels of performance, in terms of mechanical resistance, are required. In several areas of the country, the percentage of aggregates satisfying, for example, the LA_{30} category is quite reduced. This situation is exacerbated when it is necessary to satisfy both this requirement and, at the same time, to provide a good performance in terms of resistance to polishing, for example, to satisfy the PSV_{50} category. In some regions, using only alluvial aggregates, for which the project owners have serious restrictions, it is possible to ensure compliance with such requirements. Mechanical properties are almost exclusively dependent on the nature of the raw material, so the producer cannot obtain a quality gain that allows moving from one category to another, two levels upwards.

The standardisation activity for aggregates requires special attention to all its implications. Comparing the data provided by producers with the data from previous studies (Branco et al. 2006; Freire and Antunes 2007), it was concluded that the few discrepancies observed do not go beyond the adjacent category. Given the various commercial and legal constraints under which producers have to work, the overstatement or understatement of aggregate performances in technical data sheets are to be expected, and the results of this study should therefore be viewed as indicative. With the aim of improving the study, a new inquiry targeting the producers of aggregates started in October 2015, intended to understand the evolution of aggregate production and to consolidate the characterisation of the aggregates produced in Portugal. If similar works were developed, in particular in the EU, a wide database could be very useful for the creation of new standards and for the revision of aggregate standards more broadly. This aspect gains relevance when the objective is the establishment of recommendations for the definition of reasoned rejection/acceptance limits, taking into account the effective needs of the different end uses and the real production capacity in different regions. The diversity of rocks and products must be characterised and regulated in order to guarantee quality to the consumer.

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Compliance with ethical standards

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